Superconductivity of semiconductor superlattices based on lead chalcogenides

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(Submitted 8 June 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **48**, No. 2, 100–102 (25 July 1988)

Superconductivity has been detected for the first time in multilayer periodic structures based on lead chalcogenides. The critical temperature of these structures is $T_c \leqslant 4.5$ K, which is high for semiconductors. The superconductivity, two-dimensional in nature, occurs as a result of the presence of ordinary grids of misfit dislocations—dislocation superlattices—at the interfaces.

The lead chalcogenides (PbTe, PbSe, and PbS) are narrow-gap semiconductors which exhibit a superconductivity at $T < 1.0$ K when heavily doped with acceptors.[1] They have a simple cubic lattice of the NaCl type. Epitaxial films of these chalcogenides are extremely adaptable to technological processing and can serve as convenient models for high-temperature superconductors, which are close structural analogs. The layered nature of the structure of high-temperature superconductors can be modeled easily by means of superlattices consisting of thin layers of two lead chalcogenides. Superlattices are produced in an oil-free vacuum of 10^{-4}–10^{-5} Pa through the vapor deposition of lead chalcogenides and their sequential condensation on (001)KCl and (111)BaF_2 surfaces at temperatures of 550–650 K. We synthesized PbTe–PbS, PbTe–PbSe, and PbSe–PbS superlattices with layers ranging in thickness from 1 nm to 30 nm and with periods ranging from 2 to 20. We also synthesized some single-layer films as control samples, with thicknesses equal to the total thicknesses of the corresponding superlattice layers. Electron microscopy revealed that in the (001) orientation the lead chalcogenides grow in a layer-by-layer fashion on top of each other (by the Frank–van der Merwe mechanism), and a square grid of edge misfit dislocations forms at the interface with a period of 13 nm (PbSe–PbS), 8.6 nm (PbTe–PbSe), or 5.2 nm (PbS–PbSe).[2] In the (111) orientation, the growth occurs by the Volmer–Weber island mechanism, without the formation of misfit dislocations at the interfaces in the multilayer structures. The periodicity and the regularity of the superlattices were checked on the basis of satellite reflections on x-ray diffraction patterns.[3] The error in the determination of the thicknesses of the layers was no worse than 0.1 nm.

The temperature dependence of the electrical conductivity σ, the Hall coefficient R_H, and the anisotropy of the transverse magnetoresistance was studied in dc measurements over the temperature range $T = 300$–1.5 K and in magnetic fields H up to 15 kOe. The samples had the shape of a double Hall cross; the current $\mathbf{j}$ was directed parallel to the superlattice layers and satisfied the condition $\mathbf{j} \perp \mathbf{H}$. In a study of the $\sigma(T)$ dependence of the superlattices, we observed superconducting transitions at

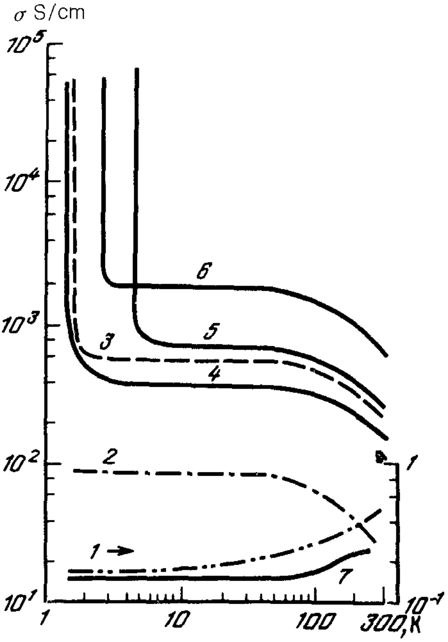

FIG. 1. Temperature dependence of the electrical conductivity σ of the samples. 1—PbTe/(001)KCl, with a thickness $d = 140$ nm; 2—PbS/(001)KCl, $d = 150$ nm; 3—PbTe-PbS/(001)KCl superlattice with layer thicknesses of 9 nm (PbTe) and 9 nm (PbS), and $N = 7$ periods; 4—PbTe-PbS/(001)KCl superlattice with layer thicknesses of 1.2 nm (quasipseudomorphic PbTe) and 14 nm (PbS) and $N = 40$; 5—PbTe-PbS/(001)KCl superlattice with layer thicknesses of 15 nm (PbTe) and 16 nm (PbS) and $N = 9$; 6—PbTe-PbS/(001)KCl superlattice with layer thicknesses of 17 nm (PbTe) and 18 nm (PbS) and $N = 10$; 7—PbTe-PbS/(111) BaF_2 superlattice with layer thicknesses of 15 nm (PbTe) and 16 nm (PbS) and $N = 16$.

$T < 5$ K, in contrast with the results found for the single-layer control films of the lead chalcogenides (Fig. 1). We took T_c to be the temperature at which the conductivity of the superlattice became equal to twice the residual conductivity σ_{res} at $T = 6$–60 K. The width of the transition, ΔT_c, was taken to be the temperature interval at which the conductivity varied over the range $(1.1$–$10)\sigma_{\text{res}}$. With an increase in H and in the current through the sample, T_c decreased, while ΔT_c increased, in the customary way for a superconductor. Further evidence in favor of a superconductivity comes from the absence of a Hall voltage for superlattice samples in weak magnetic fields, because of the complete diamagnetism, the existence of a "frozen-in" magnetic flux at $H = 0$, and the hysteretic electrodynamic effects observed during measurements of the magnetoresistance upon a change in the polarity of the magnetic field.

It was found that the highest values of T_c are exhibited by the PbTe–PbS/(001)KCl superlattices (the lattice mismatch of the layers is $f = 8.3\%$). The average Hall concentration of electrons in these superlattices was $n_{\text{H}} = (1\text{–}5) \times 10^{19}$ cm^{-3}, while their mobility $\mu_{\text{H}} = \sigma P_{\text{H}}$ did not exceed 300–1200 cm^2/(V·s). For the PbSe–PbS/(001)KCl superlattices [$f = 3.1\%$, $n_{\text{H}} = 2 \times 10^{18}$ cm^{-3}, $\mu_{\text{H}} = 1700$ cm^2/(V·s)] we observed only a slight growth of the conductivity at $1.5\ \text{K} < T < 2.3$ K: $\sigma(1.5\ \text{K})/\sigma_{\text{res}} = 1.35$. In the magnetoresistance, it was possible to see a contribution from the scattering of electrons by superconductivity fluctuations: a contribution of the Maki–Thompson quantum correction.[4] For the PbTe–PbSe/(001)KCl superlattice [$f = 5.2\%$, $n_{\text{H}} = 10^{18}$ cm^{-3}, $\mu_{\text{H}} = 2000$ cm^2/(V·s)] at $T < 3.5$ K we again observe a slight fluctuational growth of the conductivity, $\sigma(1.5\ \text{K})/\sigma_{\text{res}} = 1.5$, with a corresponding contribution to the magnetoresistance. For the PbTe–PbSe/(001)KCl

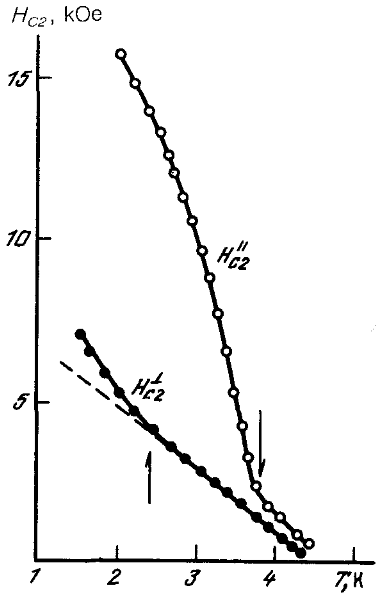

FIG. 2. Temperature dependence of the second critical magnetic field H_{c2} for a PbTe-PbS/(001)KCl superlattice (sample 5 in Fig. 1). $H^{\parallel}_{c2}$—the magnetic field lies in the plane of the superlattice layers; $H^{\perp}_{c2}$—perpendicular to the superlattice layers.

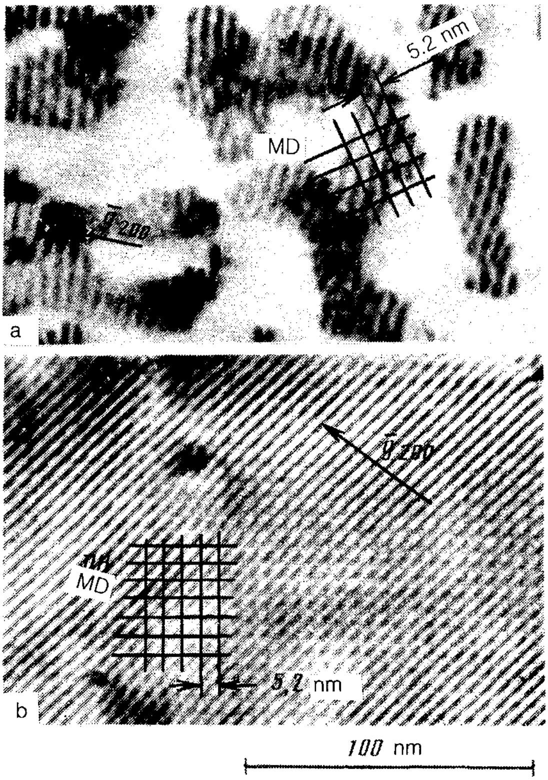

FIG. 3. Electron-microscope images of two-layer PbTe-PbS/(001)KCl films with PbTe-layer thicknesses of (a) 1.2 nm and (b) 15 nm. The thickness of the PbS is 16 nm. MD—Misfit dislocations; g_{200}—reflecting vector.

and PbSe–PbS/(001)KCl superlattices, with pseudomorphic PbTe and PbSe layers as thin as 2 nm (there are absolutely no grids of misfit dislocations), at $T > 1.5$ K we do not observe even a slight growth of σ. No scattering by superconductivity fluctuations is manifested in the magnetoresistance. For the PbTe–PbS/(001)KCl superlattices with thin ($\sim$1-nm) "quasipseudomorphic" PbTe layers (islands of grids of misfit dislocations separated from each other by pseudomorphic regions; Fig. 3a), we observe a superconducting transition with $T_c = 2$ K and $\Delta T_c = 1.5$ K, as is typical of zero-dimensional fluctuations in granular superconducting films.[5] The appearance of a superconductivity in superlattices of lead chalcogenides at $T > 1.5$ K thus agrees with the presence of regular grids of misfit dislocations at interfaces (Fig. 3b). This interpretation is also supported by the absence of a superconductivity for all three systems of superlattices grown on (111)$\mathrm{BaF_2}$ by the Volmer–Weber mechanism without the formation of misfit dislocations at interfaces (line 7 in Fig. 1). Figure 2 shows the temperature dependence of the second critical field H_{c2} (measured at the level of 50% of the residual resistance) for cases in which H is parallel to, $H_{c2}^{\parallel}$, and perpendicular to, $H_{c2}^{\perp}$, the planes of the layers of the superlattices. The pronounced anisotropy in H_{c2} and the linear nature of $H_{c2}^{\parallel}(T) \sim (T_c - T)^{1/2}$ at $T < 3.8$ K are evidence that the superconductivity is of a two-dimensional nature. On the $H_{c2}^{\parallel}(T)$ curve at $T = 3.8$ K we can clearly see a crossover to the three-dimensional situation, in which, at 3.8 K $< T <$ 4.5 K, the coherence length ξ becomes greater than the size of a single period of the superlattice but smaller than the thickness of the overall superlattice.[6] The nonlinear dependence $H_{c2}^{\perp}(T)$ at $T < 2.5$ K can apparently be linked with an effect of the periodic potential of misfit dislocations on this quantity. The basic parameter values characteristic of the PbTe–PbS/(001)KCl superlattice with the highest value, $T_c = 4.5$ K (line 5 in Fig. 1), are as follows: $n_{\mathrm{H}} = 1.2 \times 10^{19}$ cm^{-3}, $\mu_{\mathrm{H}} = 370$ $\mathrm{cm}^2/(\mathrm{V\cdot s})$, an electron mean free path $l = 18$ nm, $\partial H_{c2}^{\perp}/\partial T = 2$ kOe/K, $\partial H_{c2}^{\parallel}/\partial T = 14$ kOe/K, $H_{c2}^{\perp}(0) = 14$ kOe, $H_{c2}^{\parallel}(0) = 25$ kOe, $\xi^{\parallel}(0) = (\Phi_0/2\pi H_{c2}^{\perp}(0))^{1/2} = 19$ nm, $\xi^{\perp}(0) = \Phi_0/2\pi\xi^{\parallel}(0) H_{c2}^{\parallel}(0) = 6$ nm.

A superconductivity along dislocation superlattices has thus been observed for the first time.

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Translated by Dave Parsons